

Modeling Muscle Fatigue

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Goals

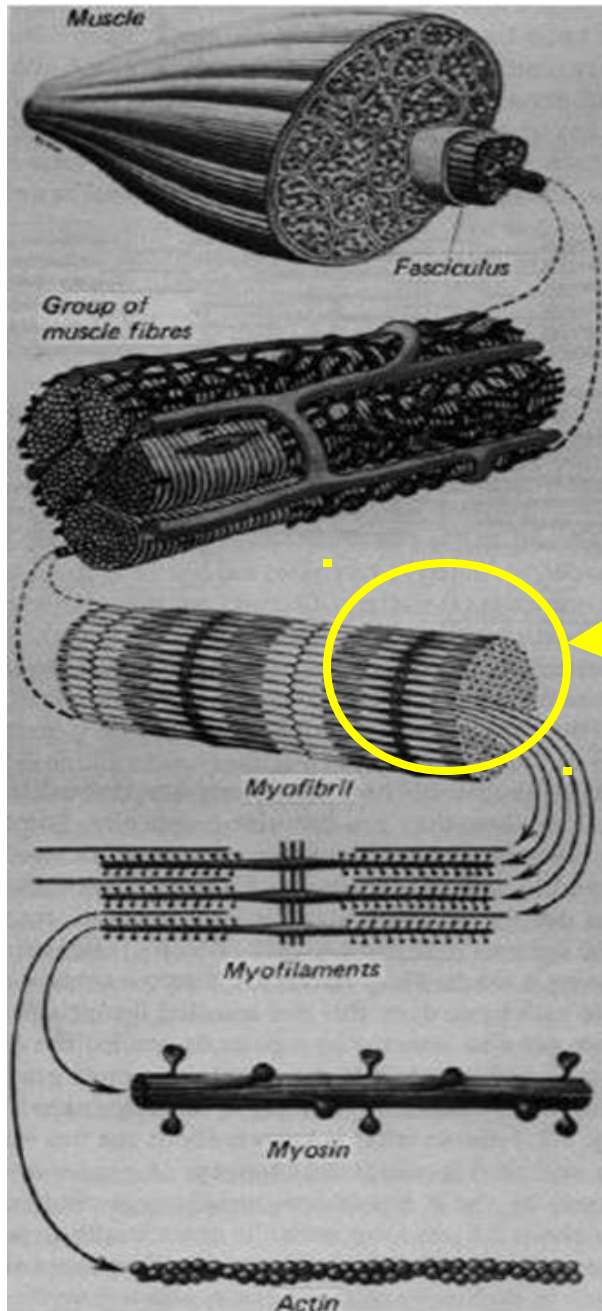
- ✓ Incorporate muscle fatigue into digital human
- ✓ Use fatigue as cost function to predict motion and posture
- ✓ Research team:
 - ✓ Faculty: Ray Han & Asghar Bhatti
 - ✓ Students (graduated): Ryan Vignes, Nate Horn



- ✓ 1930s: A.V. Hill - Related muscle heat production to force generation
- ✓ 1950s: Huxely - Sliding filament theory (electron microscopy)
- ✓ 1980s: Zajac - Added tendon and muscle pennation (extension of Hill)
- ✓ 2000: Ding-Wexler - Mechanical model with physiologically based activation



Components of a Muscle



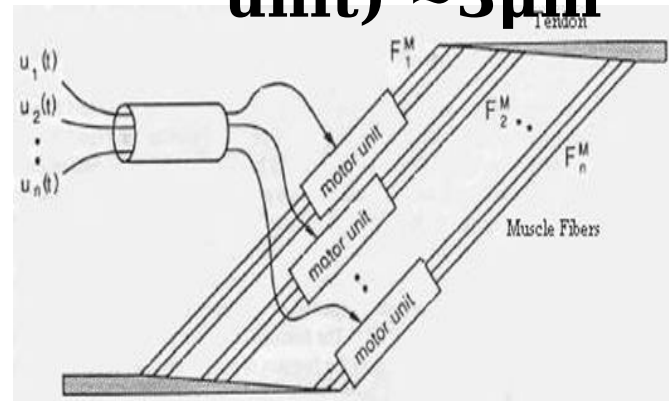
Tendon



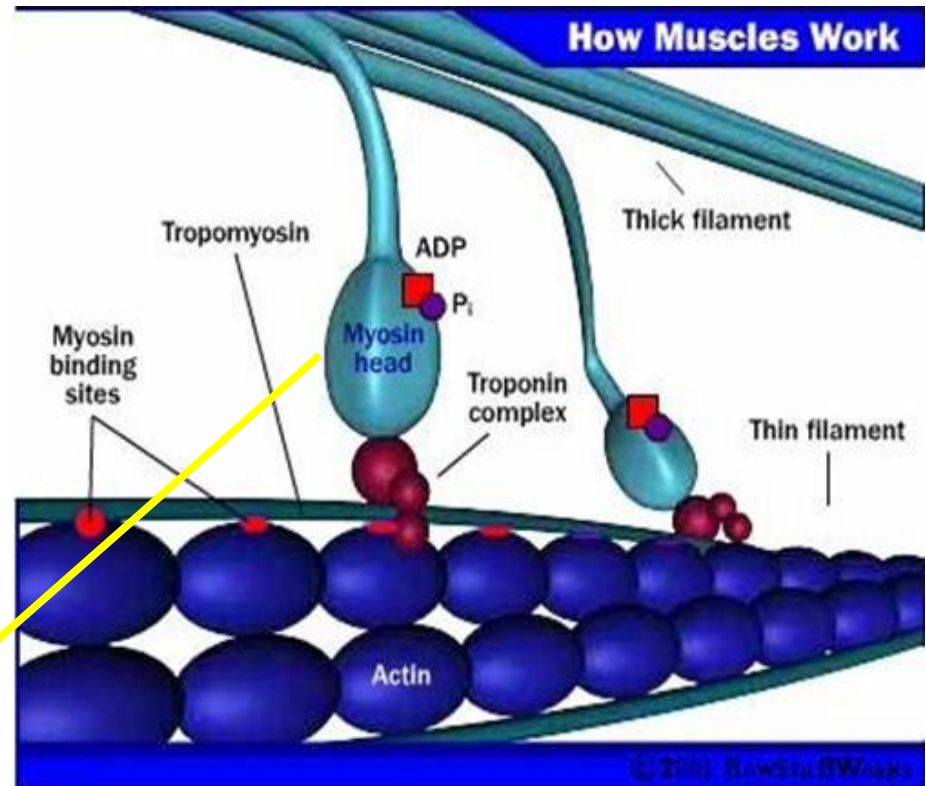
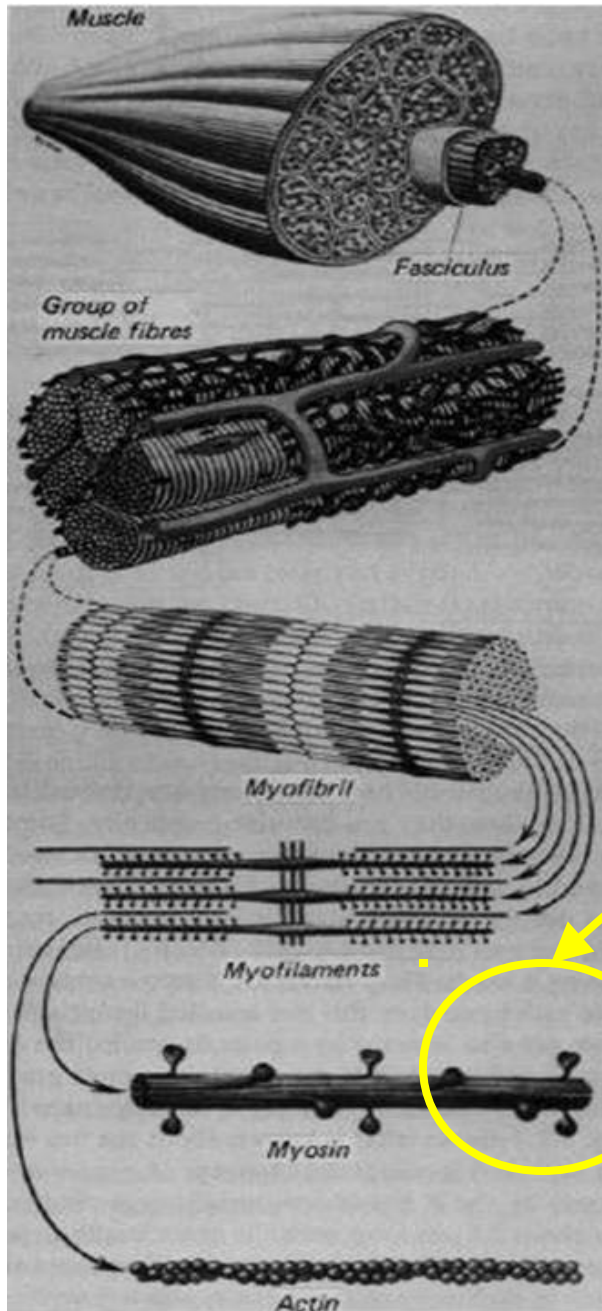
Tendon plate

Fiber

Sarcomere (force generating unit) $\sim 3\mu\text{m}$



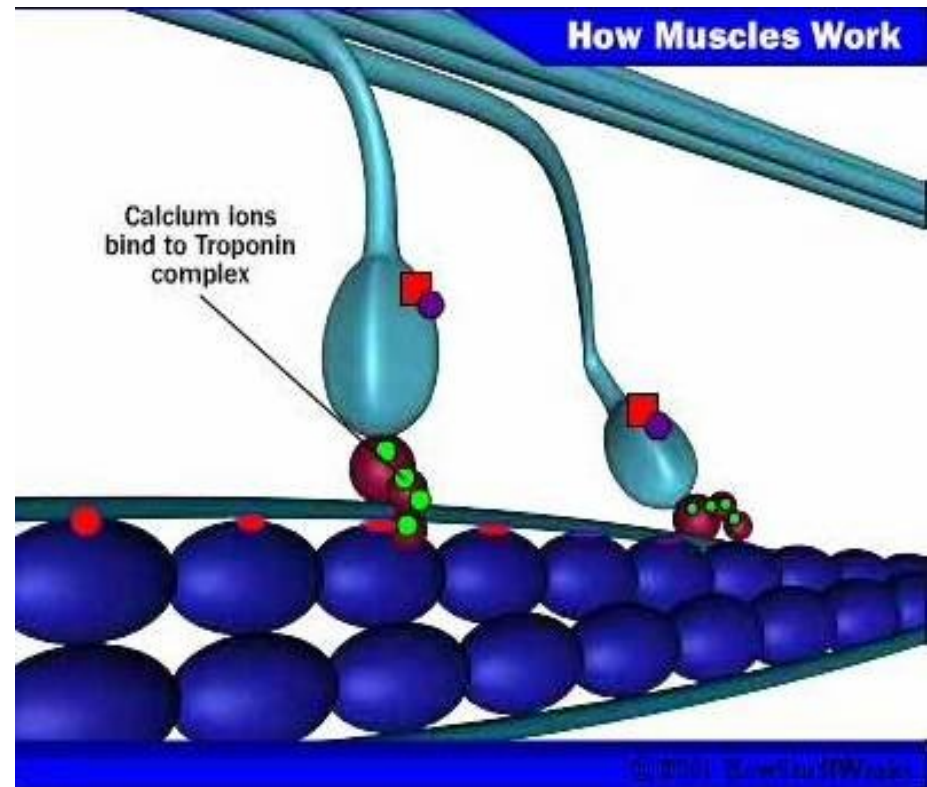
Contraction mechanism



Myosin Head - a few nanometers

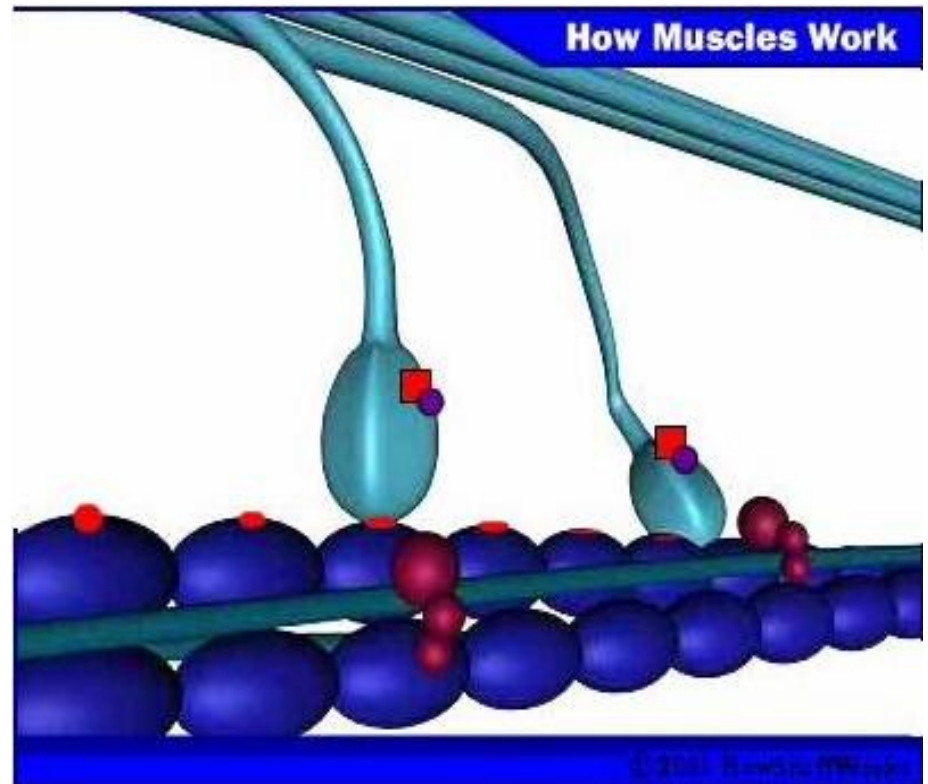
Triggering contractions

- ✓ Introduction of calcium
- ✓ Troponin and tropomyosin shift, exposing binding sites
- ✓ Myosin heads bind/move actin filament
- ✓ Chemicals released during contraction
- ✓ ATP causes myosin heads to release



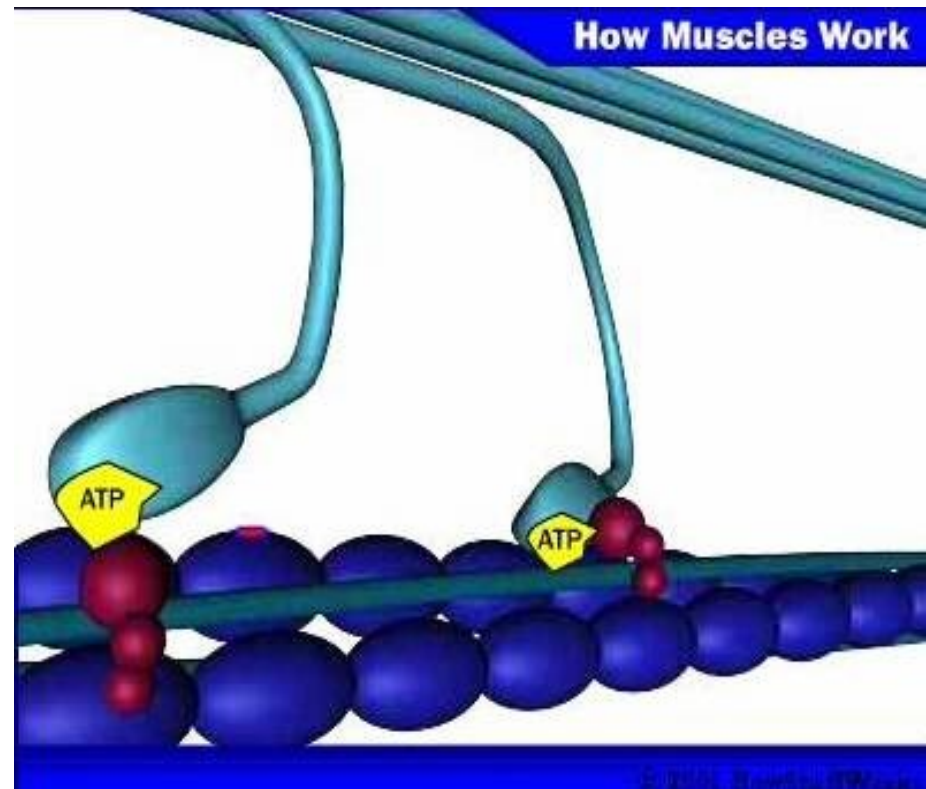
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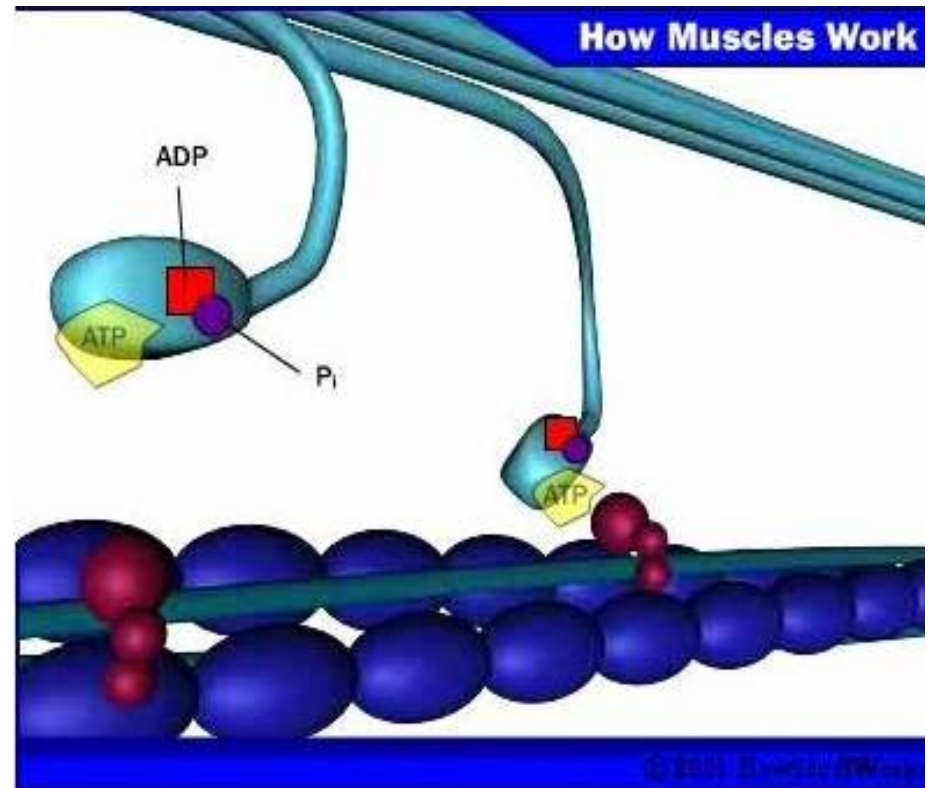
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Ding-Wexler's Model

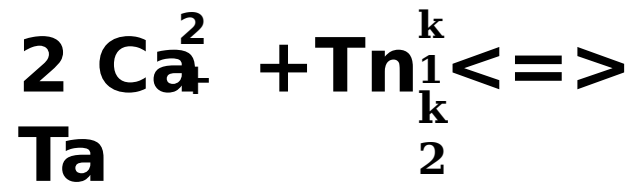
- ✓ Based on calcium fluxes and binding rates
- ✓ Combines Huxley cross-bridge theory with Hill's mechanical model

Calcium

flux:

$$J = \frac{k_1 [Ca_s]^2 - k_2 [Ca_p]}{(k_1 + k_2) [Ca_s]}$$

Calcium binding/unbinding to troponin:



Activation dynamics

$$\frac{d[\text{Ca}^{2+}]_{\text{SP}}}{dt} = 2 (k_1[\text{Ca}^{2+}]_{\text{SP}}^2 + k_2)[\text{Ta}] - 2 k_1[T_o][\text{Ca}^{2+}]_{\text{SP}}^2 + k[\text{Ca}^{2+}]_{\text{SR}} - (k + k_o)[\text{Ca}^{2+}]_{\text{SP}}$$

$$\frac{d[\text{Ta}]}{dt} = k_1[T_o][\text{Ca}^{2+}]_{\text{SP}}^2 - (k_1[\text{Ca}^{2+}]_{\text{SP}}^2 + k_2)[\text{Ta}]$$

Force dynamics

$$\frac{dF}{dt} = A[\text{Ta}] \left(1 - \frac{F}{F_m}\right) - \frac{F}{\tau_1 + \tau_2} \frac{[\text{Ta}]}{[T_o]}$$



Activation

dynam

$$\frac{dC_N}{dt} = \frac{1}{\tau_c} \sum_{i=1}^n R_i \exp\left(-\frac{t-t_i}{\tau_c}\right) - \frac{C_N}{\tau_c}$$

$$R_i = 1 + (R_o - 1) \exp\left(-\frac{t-t_i}{\tau_c}\right)$$

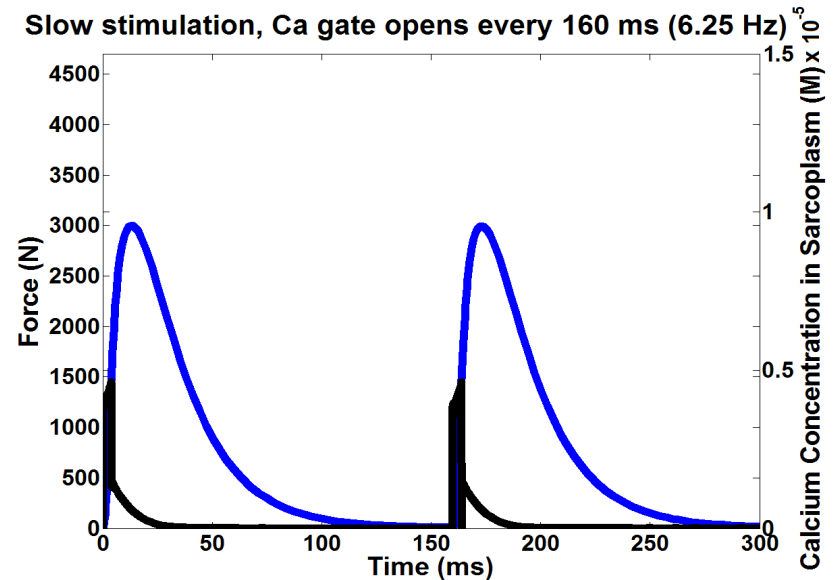
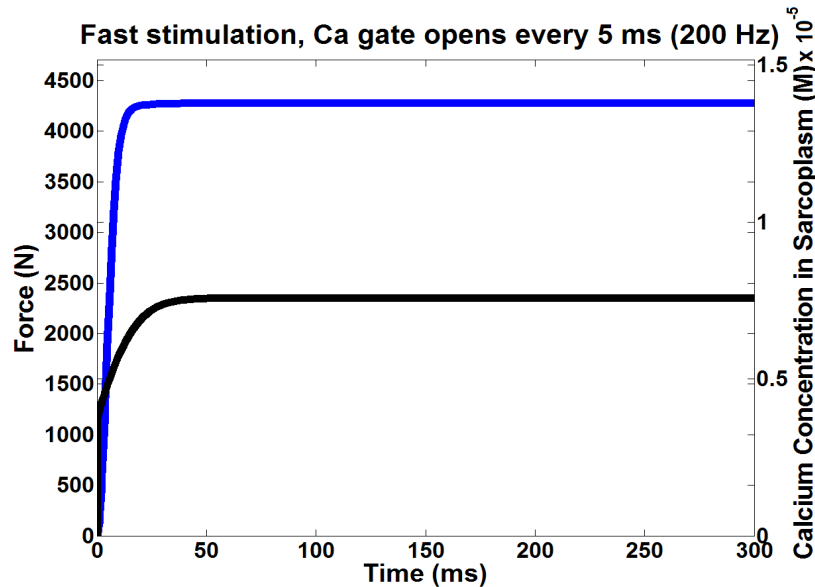
Force

dynam

$$\frac{dF}{dt} = A \frac{C_N}{K_m + C_N} - \frac{F}{\tau_1 + \tau_2} \frac{C_N}{K_m + C_N}$$

Predicted Muscle Forces

- ✓ Muscle force is a function of the stimulation rate
(the rate at which the Ca gates open)



Non-Fatigue Model

✓ A, scaling factor for force and velocity

✓ R , accounts for accumulation of Ca between stimulations

✓ τ , controls rate Ca enters muscle

$$\frac{dR}{dt} = \frac{1}{\tau_c} \sum_{i=1}^n R_i \exp \left(-\frac{t-t_i}{\tau_c} \right) - \frac{C_N}{\tau_c}$$

$$R_i = 1 + (R_o - 1) \exp \left(-\frac{t-t_i}{\tau_c} \right)$$

$$\frac{dF}{dt} = A \frac{C_N}{K_m + C_N} - \frac{F}{\tau_1 + \tau_2} \frac{C_N}{K_m + C_N}$$

Fatigue Model

$$\frac{dC_N}{dt} = \frac{1}{\tau_c} \sum_{i=1}^n R_i \exp \left(-\frac{t-t_i}{\tau_c} \right) - \frac{C_N}{\tau_c}$$

$$R_i = 1 + (R_o - 1) \exp \left(-\frac{t-t_i}{\tau_c} \right)$$

$$\frac{dF}{dt} = A \frac{C_N}{K_m + C_N} - \frac{F}{\tau_1 + \tau_2} \frac{C_N}{K_m + C_N}$$

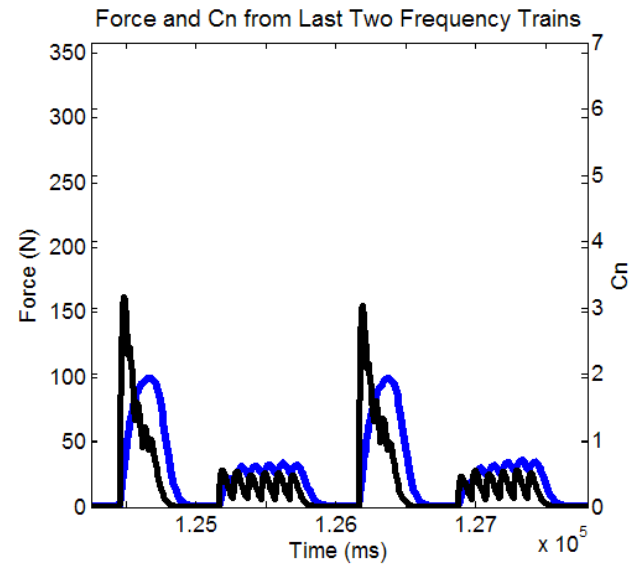
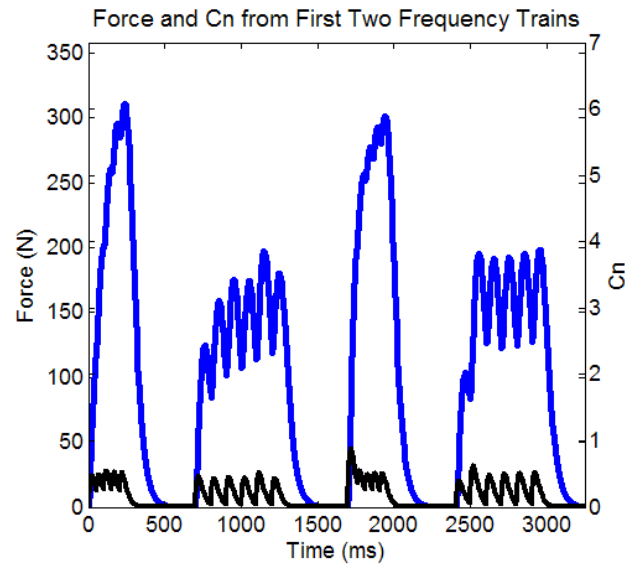
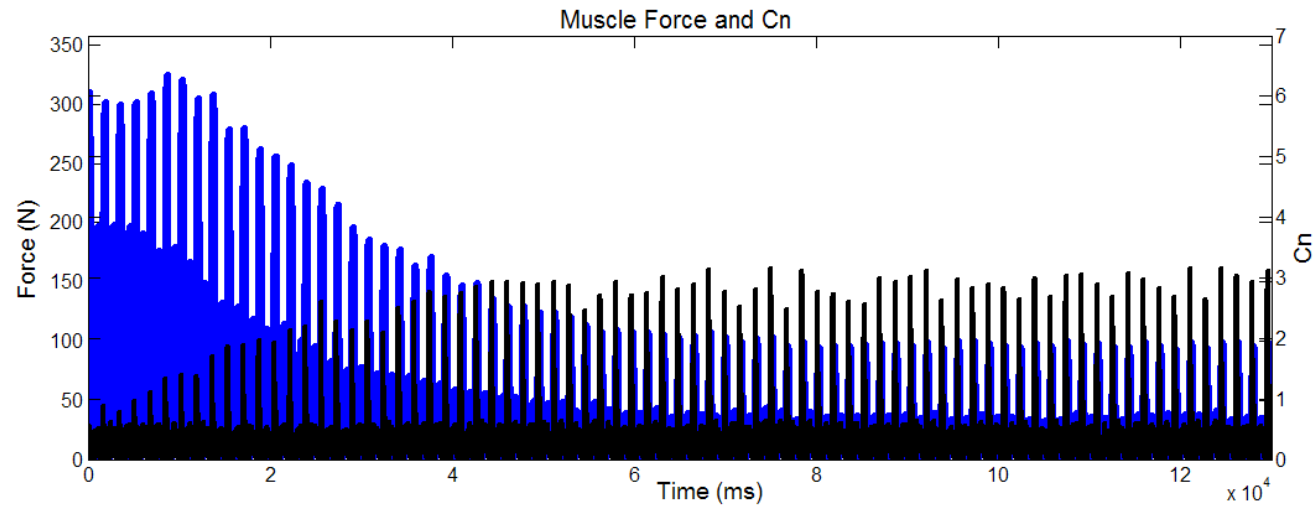
$$\frac{dA}{dt} = -\frac{A - A_{rest}}{\tau_{fat}} + \alpha_A F$$

$$\frac{dR_o}{dt} = -\frac{R_o - R_{o,rest}}{\tau_{fat}} + \alpha_{R_o} F$$

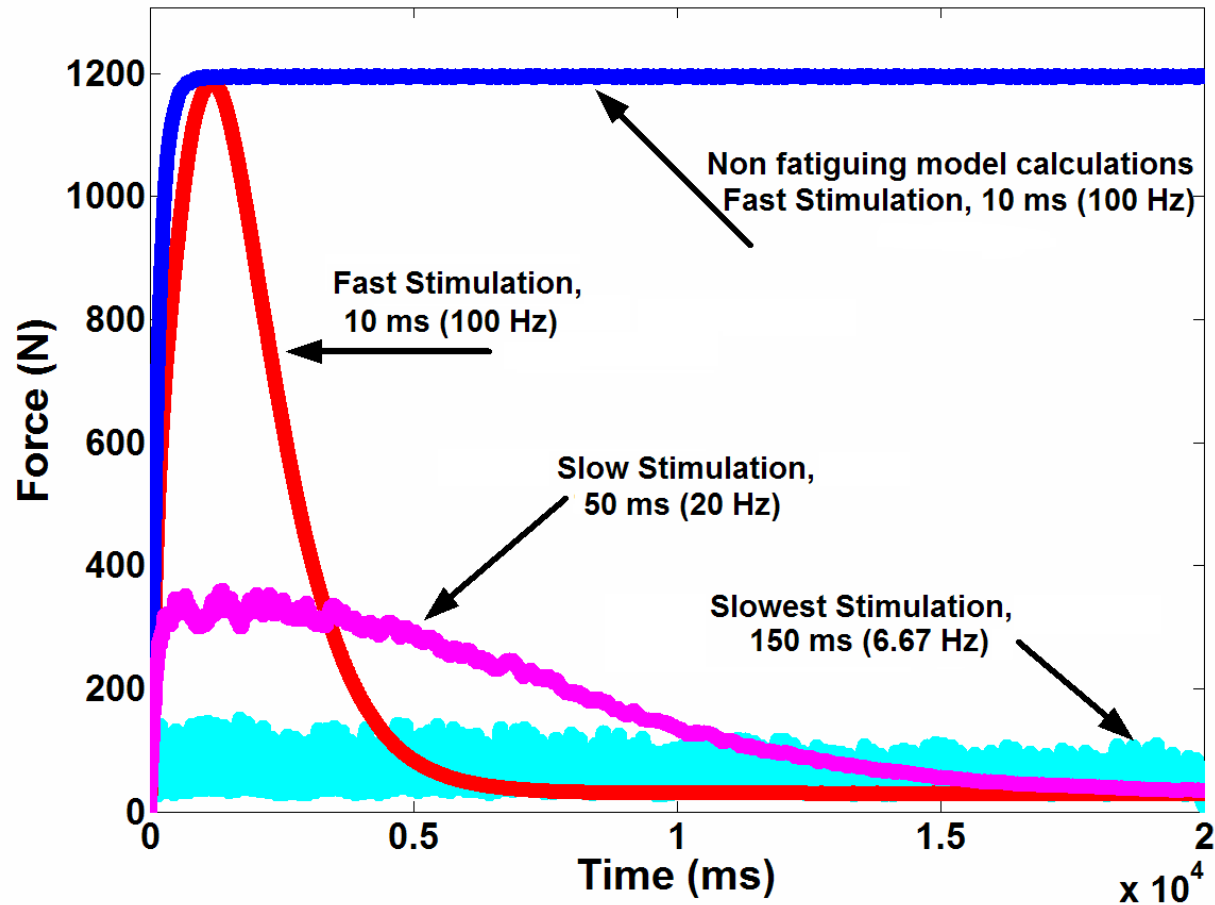
$$\frac{d\tau_c}{dt} = -\frac{\tau_c - \tau_{c,rest}}{\tau_{fat}} + \alpha_{\tau_c} F$$



Muscle force with fatigue



Force-Time Histories for Motion Simulation



Applying the Muscle Forces



- External Moment

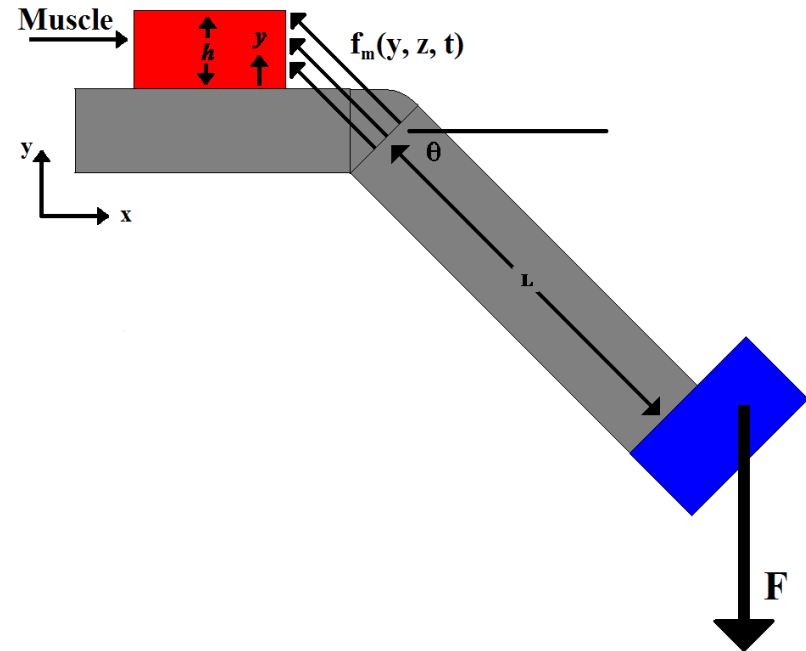
$$M_k = FL \cos [\theta(t)]$$

- Internal Moment

$$M_m = \int_0^w \int_0^h f_m(y, z, t) dy dz$$

- Moment Balance

$$\frac{d}{dt} M_k = M_m$$



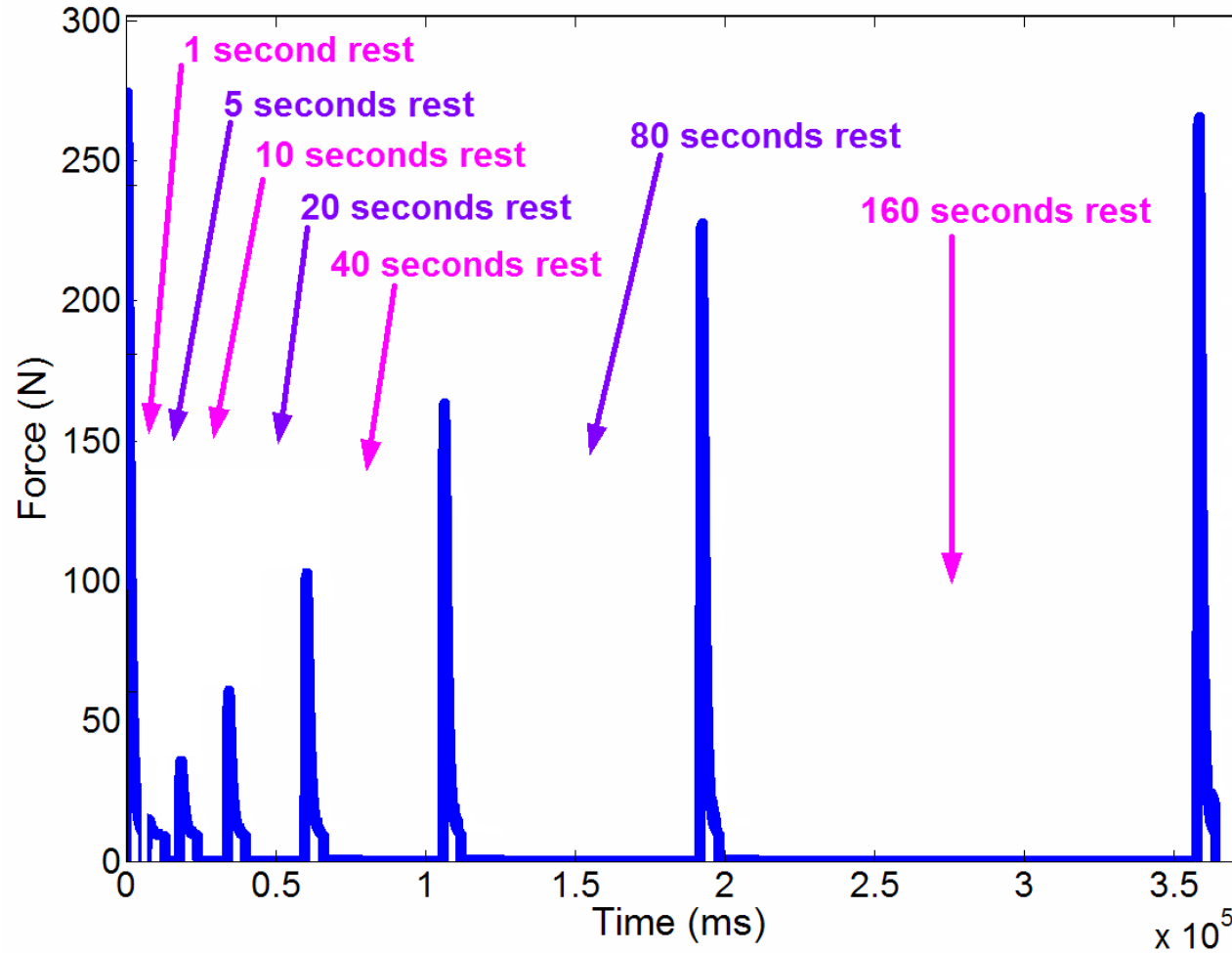
Animations

- ✓ No fatigue
- ✓ Fast Fatigue
- ✓ Slow Fatigue



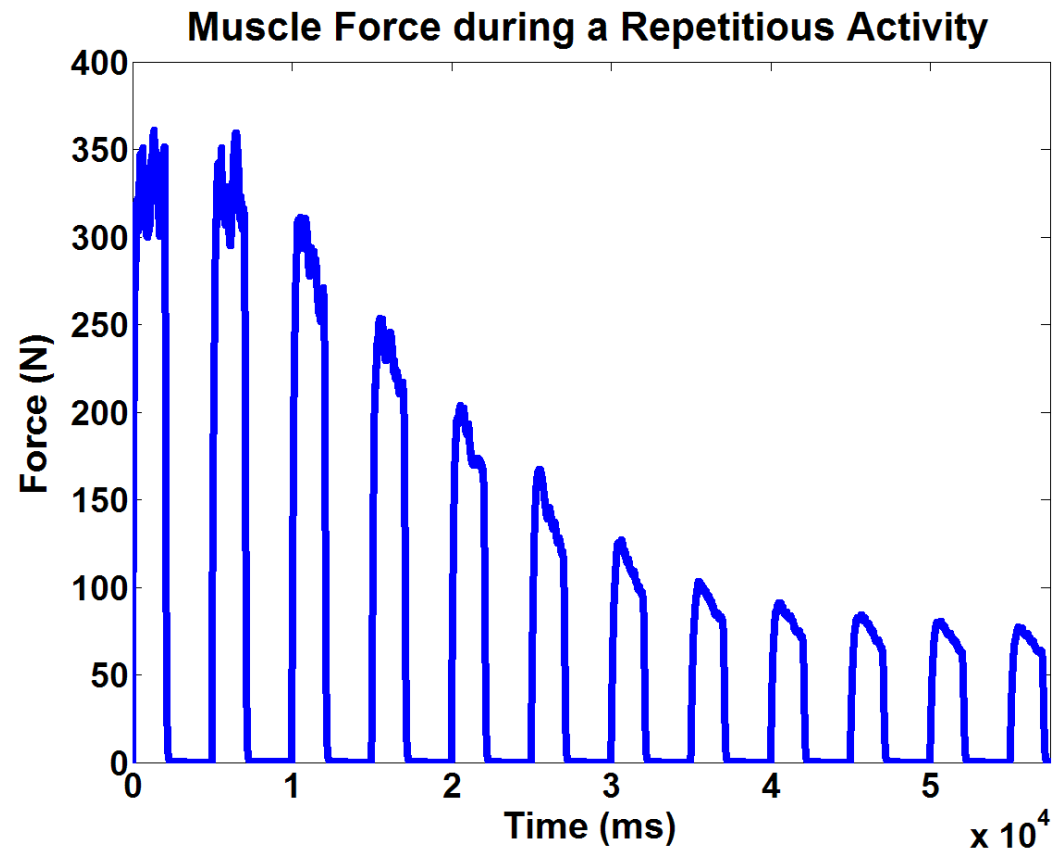
Rest between stimulations

Fatigue recovery with pulses at 10 ms

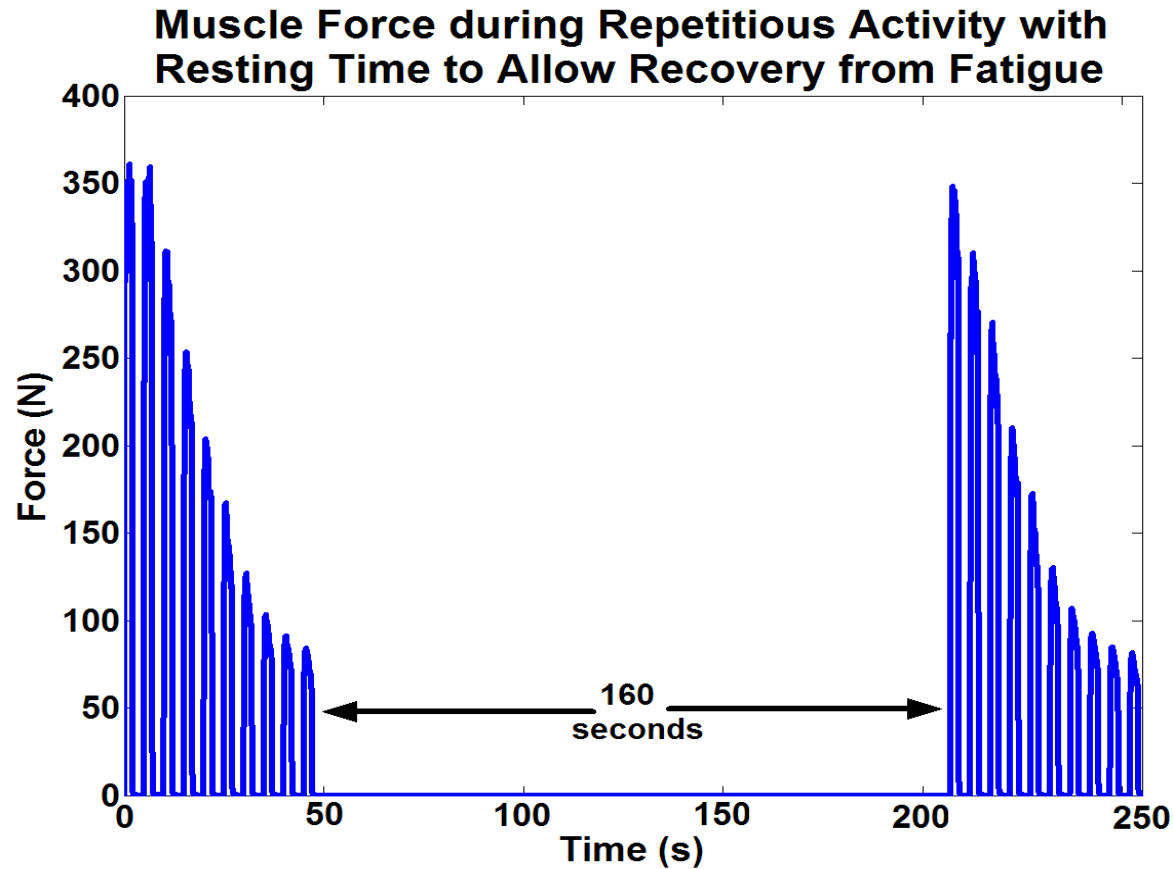


Repetitive activity

✓ Animation



Full recovery

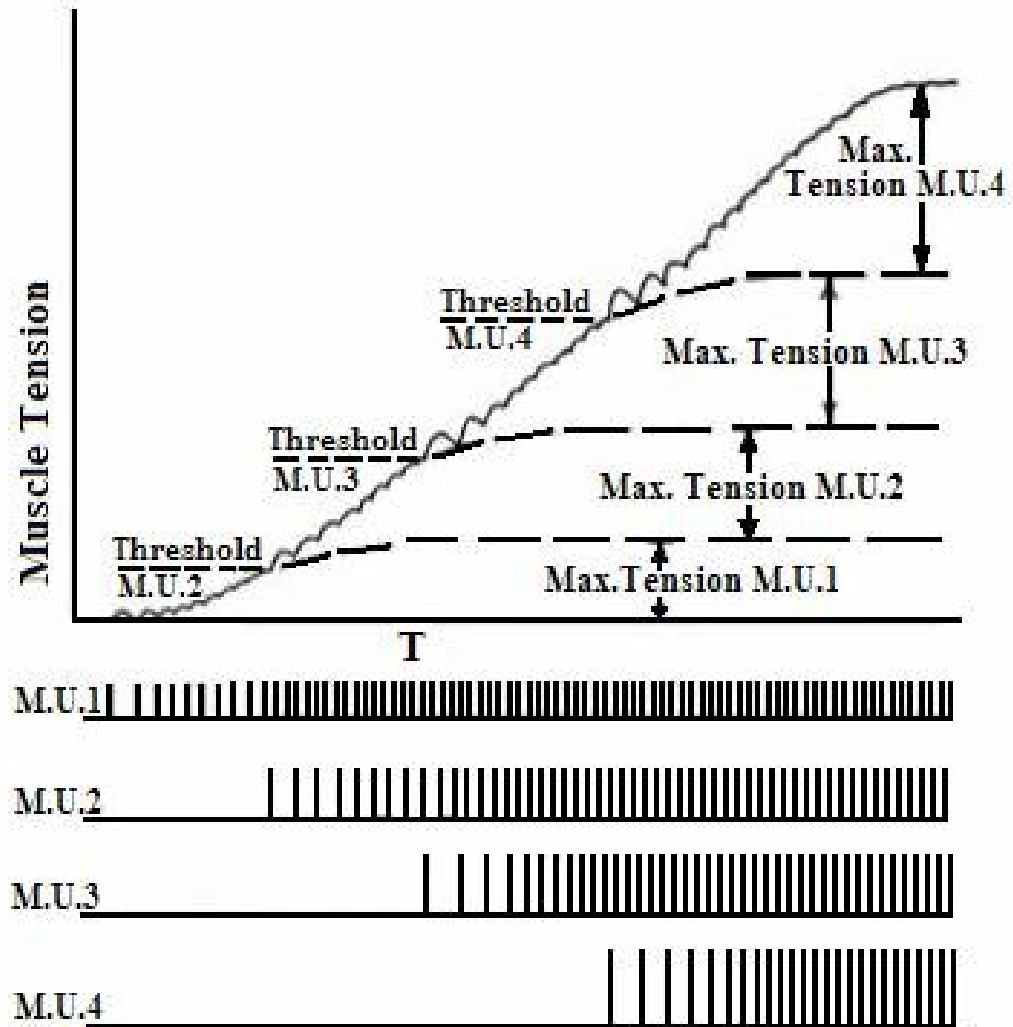


Motor Units Recruitment

- ✓ Assumed:
entire muscle
recruited to
generate force

- ✓ Faster
fatigue

- ✓ Large force
generated



Three main fiber types

- ✓ Slow Twitch (non-fatiguing)
- ✓ Fast Twitch Recoverable
- ✓ Fast Twitch Fatigable

Typical specific tension of individual motor units in three main fiber types

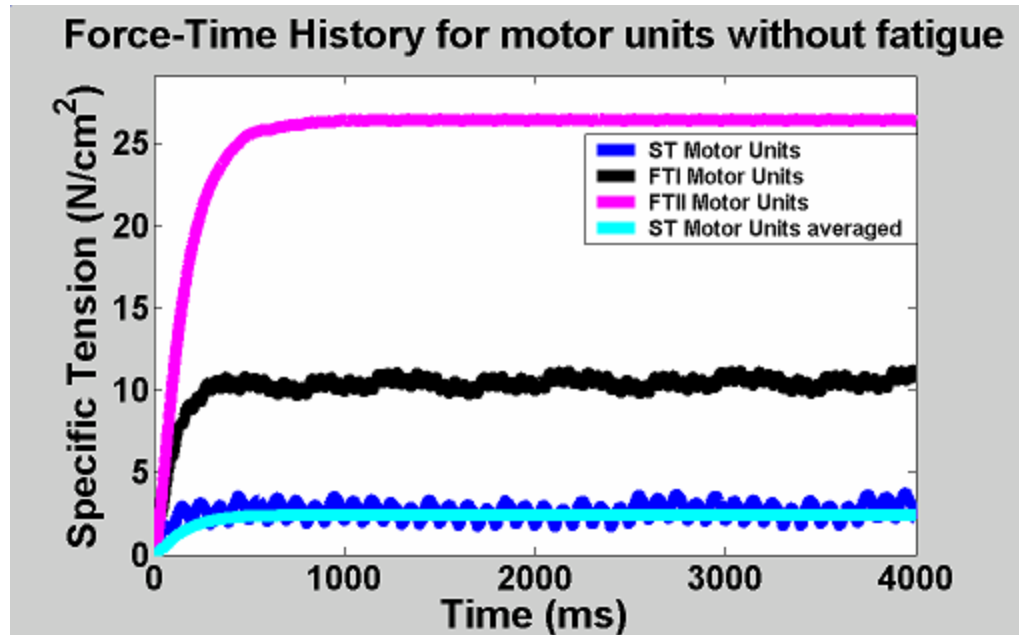
	Slow	FR	FF
Specific Tension of Fiber, ST_F	12 N/cm ²	17 N/cm ²	22 N/cm ²
Typical Fiber Area, A_f	0.01 cm ²	0.015 cm ²	0.02 cm ²
Fibers per Motor Unit, n	20	40	60

Motor unit forces

Slow Twitch	Fast Twitch Recoverable	Fast Twitch Fatigable
2.4 N	10.2 N	26.4 N



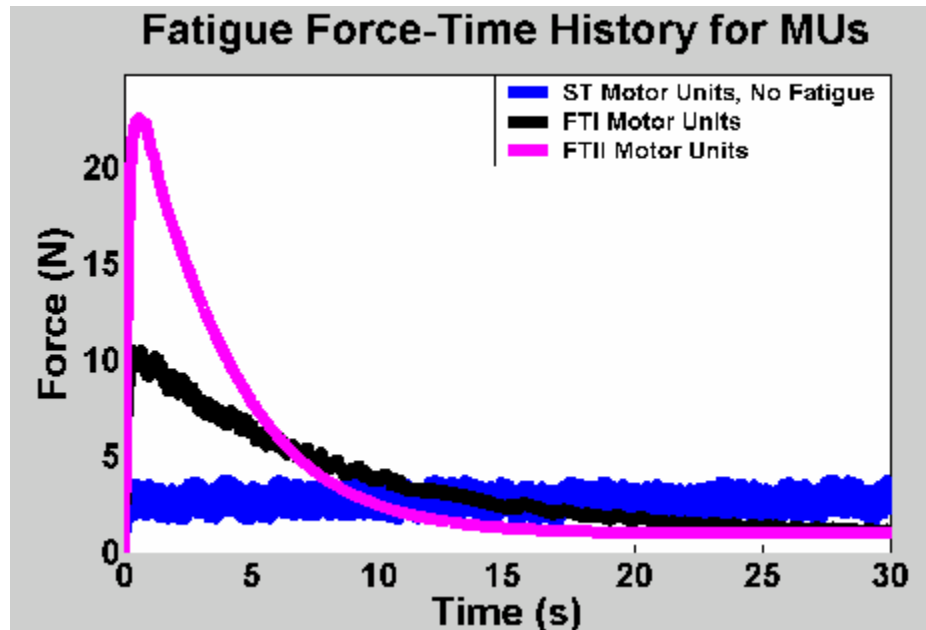
Motor units (no fatigue)



Motor unit forces

Slow Twitch	Fast Twitch Recoverable	Fast Twitch Fatigable
2.4 N	10.2 N	26.4 N

Motor units - Fatigue



Motor units recruitment

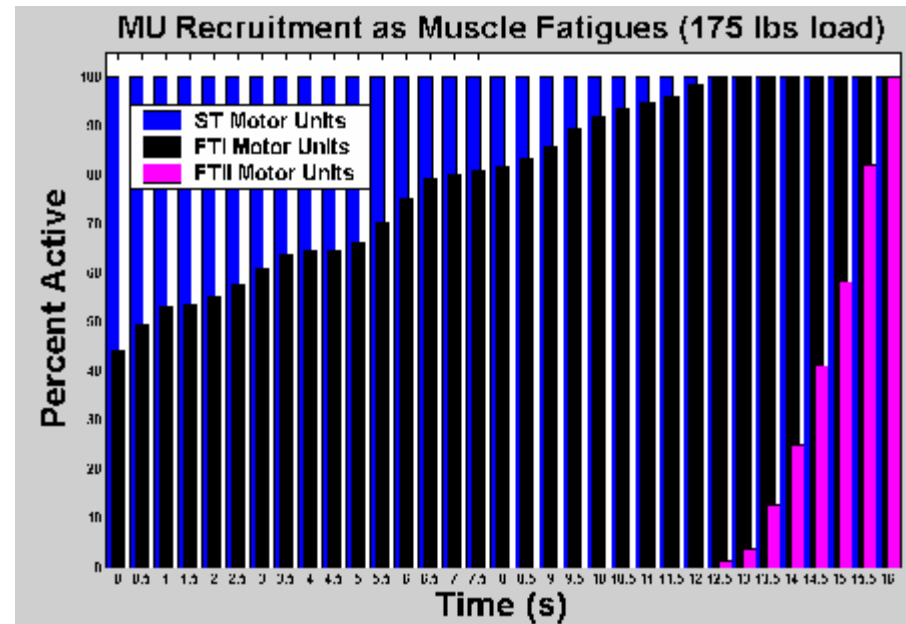
Each muscle is made up of a certain % of types of motor units.

50% *Slow*

40% *Intermediate*

10% *Fast*

✓ The recruitment of motor units to maintain a constant force as motor units begin to fatigue. Fatigue will only occur if the force is large enough to require some of the FTI or FTII motor units to be initially active. As the motor units fatigue, more are recruited until 100 % of the FTII motor units are active, after which the muscle has fatigued and the activity can no longer be performed



Remaining tasks

- ✓ Refinement of recruitment logic
- ✓ Verify predictions using EMG
- ✓ Develop cost/constraint functions for use in Santos

